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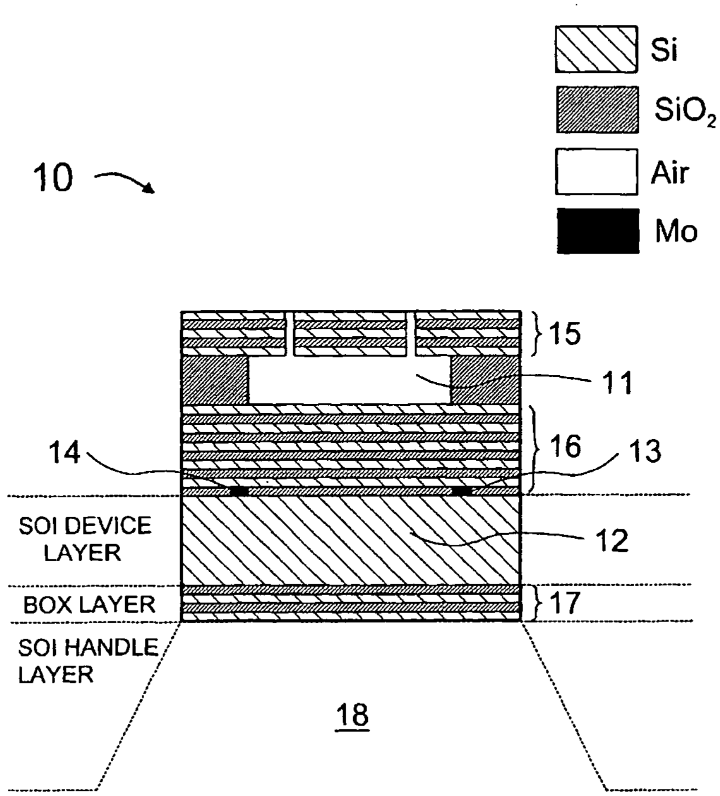
(54) Title: ELECTRICALLY TUNABLE INTERFEROMETRIC FILTER



(57) Abstract: The invention relates to a hybrid interferometric filter device (10) manufactured as a layered structure on a substrate and comprising multiple, individually electrically tunable optical resonator cavities (11, 12) arranged on top of each other on a common optical axis. According to the invention said device (10) comprises at least a first type optical resonator cavity (11) having electrostatic means for tuning the optical length of said cavity (11) by changing the distance between the end mirror elements (15, 16) of said cavity (11), and a second type optical resonator cavity (12) having thermal means (13, 14) for tuning the optical length of said cavity (12) by changing the temperature, and accordingly the refractive index of the cavity medium of said cavity (12). The device according to the invention may be used for example as an electrically tunable component in WDM systems, such as a WADM device.

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For two-letter codes and other abbreviations, refer to the "Guidance Notes on Codes and Abbreviations" appearing at the beginning of each regular issue of the PCT Gazette.

ELECTRICALLY TUNABLE INTERFEROMETRIC FILTER

The present invention relates to an electrically tunable interferometric filter device according to the preamble of the appended claim 1.

The invention is intended to be used as a compact tunable optical filter especially in optical network applications.

Traditionally tunable interferometric Fabry-Perot devices have been used as modulators or analysers in a wide variety of optical systems. Silicon-surface micromachining is a recent technology which provides expanding possibilities to manufacture miniature or microscopic optical devices, which also include interferometric structures like Fabry-Perot cavities. Silicon-surface micromachining has also been used for manufacturing micro-opto-electro-mechanical systems (MOEMS), which can be further used to realize miniature-size electrically controllable optical devices. Due to their small physical size and silicon-based construction, MOEMS devices can be readily integrated into modern optical systems, which are based on optical fibers and/or other optical waveguides. The recent rapid development of optical telecommunication and optical data processing systems creates increasing needs for versatile electrically controllable optical devices, which can be used for modulation and/or spectral filtering of light in optical networks.

WO patent application 98/14804 describes an optical bandpass filter, which comprises two electrically controllable, silicon-surface micromachined Fabry-Perot resonant cavity filters, which are fixed on a common optical axis to form a double-cavity optical filter. The obvious benefits of the double-cavity structure over a traditional single cavity design are the wider possibilities to tune the shape and the position of the transmission peak in wavelength domain by tuning individually and separately the two successive resonator cavities.

The structure of the double-cavity filter described in WO 98/14804 is based on having two separate interferometric air-filled (or more generally gas-filled) cavities fixed in series in a manner that the length

of said cavities, i.e. the physical distance between the end mirrors in each cavity can be electrostatically tuned. Each of the air cavities comprises two end mirrors, i.e. the double-cavity construction comprises altogether four separate mirrors. In order to physically couple the two resonator cavities together, a special mirror element is used in between the cavities. Said mirror element comprises two separate mirror members, which have an optically matching layer, advantageously a layer of air or vacuum, adapted thereinbetween. The first mirror member of said mirror element thus acts as an end mirror for the first resonator cavity, and the second mirror member acts as an end mirror for the second resonator cavity, respectively. It will be apparent for any person skilled in the art that in order to perform in a desired manner, both of the separate air cavities have to be carefully tuned and also maintained in tune during the use.

Problems in the double-cavity filter structure manufactured on silicon and described in WO 98/14804 arise mainly from the fact that the maximum physical length of the air cavities is in practice rather limited due to the manufacturing difficulties. The physical length of the cavity, which also defines the effective optical length of the cavity, should be accurately controlled during the manufacture. In practice, this becomes more difficult with increasing cavity lengths, and beyond 3 μm it becomes typically unfeasible. This severely limits the manufacture of resonator cavities for certain applications. A person skilled in the art will be familiar with the fact that the separation of adjacent transmission peaks in a Fabry-Perot resonator cavity, i.e. the so-called free spectral range of the cavity is governed by the optical length of the cavity, which is further directly linked with the physical length of the cavity. The width of the transmission peaks is governed by the reflectivity of the end mirrors together with the optical length of the cavity. In practice, the double-cavity filter with two separate air-filled cavities and electrostatic tuning is very challenging to tune and especially to maintain in tune during the actual use of the device. If either one of the cavities becomes only slightly tuned off from the optimum, the optical losses increase significantly and the transmission peak broadens and/or drifts in wavelength domain.

The main purpose of the present invention is to produce a novel electrically tunable double- or multi-cavity interferometric filter device, which does not suffer from the aforementioned limitations to the same degree as prior art devices. Further, the device according to the invention is also simpler in construction, and the resonator cavities are more closely coupled, thus facilitating an advantageous filter device which, in addition to being easier to manufacture, is also easier to tune and maintain in tune than the devices of prior art.

To attain these purposes, the device according to the invention is primarily characterized in what will be presented in the characterizing part of the independent claim 1.

The basic idea of the invention is to combine two different types of electrically tunable interferometric resonator cavities into a hybrid multi-cavity filter structure. According to the invention, the first type of resonator cavities includes such structures in which the cavity is arranged to be tuned electrostatically by changing the physical distance between the end mirror elements of the cavity. The second type of resonator cavities includes such structures in which the cavity is arranged to be tuned thermally by changing the temperature and thereby the refractive index of the optical medium of the cavity.

The filter device according to the invention is preferably manufactured as a compact layered structure on a planar SOI (Silicon-On-Insulator), i.e. as a MOEMS device.

In a preferred embodiment of the invention, the filter device is a double-cavity filter in which the cavity medium of the first resonator cavity is a gas, preferably air, and the cavity medium of the second resonator cavity is a suitable optically transparent material, preferably silicon. The use of a solid material such as silicon in the second cavity provides the possibility to make significantly longer cavity lengths than that of the state of the art without sacrificing the cavity manufacturing or tuning accuracy. The thermal tuning of the second resonator cavity also provides a much higher tuning accuracy than that achieved using electrostatic tuning, which affects the physical length of the cavity. The

change of the temperature of the optical medium of the second resonator cavity naturally also changes slightly the length of said cavity due to the thermal expansion, but for example in the case of silicon, the change of the refractive index of the cavity (due to the temperature change) dominates clearly over the optical effects caused by the aforementioned small change in the cavity length.

The advantages of the hybrid filter structure according to the invention arise from combining the best properties of the two different types of electrically tunable interferometric filters in a new and beneficial way. The result is a compact filter device whose performance cannot be achieved by a double- or multi-cavity device based on a single type of electrically tunable filters.

The preferred embodiments of the invention and their benefits will become more apparent to a person skilled in the art through the description and examples given hereinbelow, and also through the appended claims.

In the following, the invention will be described in more detail with reference to the appended drawings, in which

Fig 1 illustrates schematically the basic structure of a device according to the invention, and

Figs 2,3 illustrate simulated transmission of a device described in Fig.1 and designed specifically to be used as a WADM module in a WDM network.

Fig. 1 depicts schematically the basic structure of a double-cavity interferometric filter device 10 according to the invention. The Fabry-Perot type structure is fabricated on an SOI wafer. The upper cavity 11 is an air cavity arranged to be tuned electrostatically and the lower cavity 12 is a silicon cavity arranged to be tuned thermally by ohmic heating. The molybdenum strips 13,14 provide the necessary means for heating the lower cavity 12. The dashed lines in Fig. 1 represent the contour of the SOI wafer on which the structure is processed. A person

skilled in the art will appreciate that Fig. 1 is not drawn to correct scale and also that the different layers and structures of the device are not presented in correct proportional scale.

The mirror elements 15,16,17 in Fig. 1 are dielectric thin film mirrors that are made by stacking thin films of materials having different refractive indexes on top of each other. Each individual layer has an optical thickness corresponding to a quarter of the wavelength of the incident light. This type of a layered thin film mirror structure, which is well known in the art, is called a Quarter Wave Optical Thickness (QWOT) filter structure. In Fig. 1 the QWOT filters 15,16,17 are realized by stacking alternating silicon (Si) and silicon dioxide (SiO_2) layers. The reflectivity of a mirror element based on a QWOT structure can be increased by increasing the number of layers in the structure. Higher reflectivity of the end mirror elements of a Fabry-Perot resonator cavity increases the finesse of the resonator, which decreases the width of the transmission peaks and provides higher contrast between the transmitted and rejected light.

In the following, the structure of the double-cavity interferometric filter device 10 will be described in more detail with reference to Fig. 1.

The dashed lines in Fig. 1 represent the contour of the SOI wafer on which the filter device is processed. The different layers in the SOI wafer are the SOI handle layer, the BOX (Buried Oxide) layer and the SOI device layer. SOI wafers are widely used in industry and are commercially available with different layer thicknesses and different resistivities.

The first mirror element 17 (a QWOT structure), denominated the first mirror element analogously to its manufacturing order, is realized using the BOX layer of the SOI wafer. An opening 18 necessary for the fabrication of the first mirror element 17 is arranged in the SOI handle layer below said first mirror element 17. The opening 18 also serves for reducing the thermal capacity of the device. A suitably designed BOX layer may itself directly act as the first mirror element 17, but typically

the original BOX layer is etched away and specific mirror layers for the first mirror element 17 are deposited.

The first mirror element 17 constitutes the lower end mirror of the thermally tunable silicon cavity 12, which cavity is made in the device layer of the SOI wafer. The upper end mirror of said cavity is the second mirror element 16 (a QWOT structure), which includes molybdenum strips 13,14 for heating and tuning of the silicon cavity 12. When the silicon material of the silicon cavity 12 is heated, the refractive index, i.e. the optical thickness of the cavity 12 increases and the tuning of the cavity changes. By applying a suitable bias temperature above the ambient temperature in the silicon cavity 12, the silicon cavity can be tuned in both directions with respect to its designed center wavelength. In other words a bias temperature above ambient temperature allows the cavity to be "cooled" or heated with respect to said temperature. An active cooling using a Peltier-element may also be used for tuning of the silicon cavity 12.

The second mirror element 16 functioning as the upper end mirror for the silicon cavity 12 simultaneously also functions as the lower end mirror for the air cavity 11. The electrostatically tunable air cavity 11 in Fig. 1 comprises the fixed lower end mirror 16 and a flexible, moving upper end mirror 15 separated by an air gap. The moving upper end mirror 15 is the third mirror element contained in the double-cavity structure illustrated in Fig. 1.

The third mirror element 15 is actuated by applying a voltage between itself and the fixed second mirror element 16. Said voltage causes the third mirror element 15 to flex toward the fixed second mirror element 16 owing to the electrostatic force created between said mirror elements. The required control voltage varies typically from a few volts up to some tens of volts. By applying a suitable bias voltage between the mirror elements 15,16, the air cavity can be tuned in both directions with respect to its designed center wavelength.

WO 98/14804 describes a number of different ways to realize a single electrostatically tunable air cavity as a part of a double-cavity structure

comprising two such cavities. It is clear for a person skilled in the art that air cavity structures described in WO 98/14804 can also be applied to realize the upper air cavity 11 of the device according to the invention.

The strength of the hybrid filter structure 10 according to the invention lies in combining the best properties of the electrostatically and thermally tunable interferometric filters into a single filter device. An important advantage of an electrostatically tunable air cavity is its large tuning range. The maximum tuning range of an air cavity 11 (or generally of a gas filled cavity) is in the order of one third of the physical length of the cavity. A disadvantage is that the maximum physical cavity length is in practice limited. On the other hand, the silicon cavity 12 (or a cavity made of some other suitable solid material) provides a possibility to implement significantly longer cavity lengths. The maximum tuning range of an thermally tunable solid cavity is smaller than that of a electrostatically tunable air cavity, but accordingly, the tuning accuracy is then also significantly better than that of an air cavity.

In the following, one specific and advantageous application of the optical filter device 10 according to the invention will be presented in order to further demonstrate the potential of the hybrid filter structure combining two different types of cavities.

It is well known that one way to increase the capacity of existing optical networks is to use Wavelength Division Multiplexing (WDM). The basic principles of WDM are well known in the art and thus not repeated here. Efficient use of WDM techniques, however, requires the capability to manipulate the paths of the optical signals purely by optical means, i.e. without performing optical-to-electrical and electrical-to-optical conversions for signal switching.

In WDM and also in Dense Wavelength Division Multiplexing (DWDM), each optical fiber (or other waveguide) transmits several optical signals (channels) separated by a certain frequency (wavelength) difference. Narrowband spectral filters are essential components to optically

remove specific channels from the network and to reinsert new ones into the network. Such optical filter modules are known as Wavelength Add/Drop Multiplexers (WADM). WADMs can range in capacity from providing dedicated add/drop of a single channel (wavelength band) to having fully reconfigurable add/drop of many wavelength division multiplexed channels. Tunable optical filters are particularly useful for reconfigurable WADMs. Important filter characteristics in WADM applications include attenuation within the transmission window, bandwidth of the transmission window, out-of-band rejection, chromatic dispersion, etc.

Fig. 2 and 3 illustrate transmission curves that have been modelled for a device having the structure shown schematically in Fig. 1 and designed specifically to be used as a WADM module in a WDM network. In Figs 2 and 3, the transmission spectrum of the double-cavity filter device 10 according to the invention is superimposed over a WDM channel grid with 200 GHz channel spacing and 40 GHz channel width.

The specific structure of the double-cavity filter device used for the aforementioned modelling corresponds to the following physical layers:

Si(111.1nm)	
Si(111.1 nm)SiO_2(267.2 nm)]^2	
Air(2.3 μm)	(air cavity)
[Si(111.1 nm)SiO_2(267.2 nm)]^5	
Si(13.3 μm)	(silicon cavity)
[Si(111.1 nm)SiO_2(267.2 nm)]^2	

Expressed in QWOT units the air cavity thickness corresponds to 6 QWOT units and the silicon cavity thickness corresponds to 120 QWOT units. A person skilled in the art appreciates that when converted to physical values (meters), the resulting thickness of the layers depends on the refractive index of the cavity material in question. In the aforementioned modelling typical refractive index values (for the wavelength 1.55 μm) available from literature have been used.

Fig. 2 shows the transmission band of the filter device 10 electrically tuned over a channel with reference (center) wavelength of 1552.52 nm. Fig 3 shows the transmission band of the filter device 10 electrically tuned over the adjacent channel spaced 1.6 nm (200 GHz) away from the aforementioned channel. This is obtained by simultaneously increasing the refractive index of the silicon cavity 12 by heating and by increasing the physical length of the air cavity 11 by electrostatically moving the third mirror 15.

From Figs 2 and 3 it can be seen that the filter device 10 according to the invention provides a small insertion loss, i.e. attenuation within the transmission window, and at the same time a good adjacent channel separation, i.e. out-of-band signal rejection (> -30 dB). Due to the double-cavity structure, the transmission profile within the transmission window is substantially flat and corresponds well to the channel width in WDM systems.

The maximum tuning range of a single WADM device according to the invention is expected to cover the wavelength range from 1520 nm up to 1610 nm. This corresponds to over 100 individual WDM channels depending on the channel spacing (for example 100 GHz = 0.8 nm, 200 GHz = 1.6 nm).

The device according to the invention shows therefore significant potential as a compact and widely tunable WADM device. It is clear that the device according to the invention may be specifically designed for a specific channel spacing (for example 25, 50, 100, 200 GHz) and/or channel width deviating from the aforementioned example. Such designs may include altering the number of the layers in the mirror elements 15,16,17 and/or changing the basic length of the cavities 11,12. The materials used in the mirrors 15,16,17 may also be changed, and for example Si_3N_4 or SiO_xN_y layers may be used. However, metallic mirrors are not preferred due to their high optical losses.

While the invention has been shown and described above with respect to certain embodiments, it should be understood that these are only examples and that a person skilled in the art could construct other optical filtering devices utilizing techniques other than those specifically disclosed herein while still remaining within the spirit and scope of the present invention.

It should therefore be understood that various omissions and substitutions and changes in the form and detail of the tunable filtering device illustrated, as well as in the operation of the same, may be made by those skilled in the art without departing from the spirit of the invention. For example, it is expressly intended that all combinations of those elements which perform substantially the same function in substantially the same way to achieve the same results are within the scope of the invention. Moreover, it should be recognized that structures and/or elements shown and/or described in connection with any disclosed form or embodiment of the invention may be incorporated in any other disclosed or described or suggested form or embodiment as a general matter of design choice. It is the intention, therefore, to restrict the invention only in the manner indicated by the scope of the claims appended hereto.

For example, even if the device according to the invention is preferably manufactured on an SOI wafer, also other semiconductor or compound semiconductor materials such as for example germanium or GaAs are possible. In principle, the substrate material can be of any material on which the deposition of mirror layers can be performed and which has optical properties compatible with the specifications of the interferometric filter device.

It is well known in the art that the transmission properties of a mirror element based on a QWOT structure can be increased by increasing the number of layers in the QWOT structure. Thus the number and thickness of the layers in the mirror elements 15,16,17 in the filter device 10 can be freely selected according to the application.

The molybdenum strips 13,14 providing means for heating the solid material cavity 12 may be replaced by strips or other suitable structures made of some other material, for example aluminium, said structures and material being suitable to be heated by ohmic (resistive) heating. Also other thermal means for altering the temperature of the solid material cavity 12, apparent for a person skilled in the art, may be applied without departing from the spirit of the invention. For example, it is possible to use local ion-doping for creating the means required for heating of the solid material cavity 12.

The embodiments of the invention are not limited to the near infrared wavelength range (1-2 μm), but within the scope of the appended claims, devices for shorter (visible) or longer (IR) wavelengths may be implemented.

The devices according to the invention may be used as spectral filters, where the tuning capability is only used to compensate for the fabrication tolerances affecting the transmission properties (shape and position of the transmission peak) of the filter. Furthermore, the tuning capability can be used to actively change the transmission properties and thus making it possible to use the device as a light modulator or analyser, or as an electrically tunable component in WDM systems, such as a WADM device.

The multi-layered structures necessary to manufacture a device according to invention may be achieved by using Low Pressure Chemical Vapour Deposition (LPCVD) processes. In LPCVD processes, gaseous precursors are allowed to react at elevated temperature (typically 300-900 °C) and at low pressure (typically 50-100 Torr). The composition of the precursors depends on the desired film. Other silicon-surface micromachining techniques such as Plasma Enhanced CVD (PECVD) may also be used.

Claims :

1. An interferometric filter device (10) manufactured as a layered structure on a substrate and comprising multiple, individually electrically tunable optical resonator cavities (11,12) arranged on top of each other on a common optical axis, said optical resonator cavities (11,12) each having a characteristic optical length, which optical length depends on the distance between the end mirror elements (15,16;16,17) of said cavity (11,12), i.e. on the physical length of said cavity (11,12), and on the refractive index of the cavity medium contained between the end mirror elements of said cavity (11,12), **characterized** in that said device (10) comprises at least

— a first type optical resonator cavity (11) having electrostatic means for tuning the optical length of said cavity (11) by changing the distance between the end mirror elements (15,16) of said cavity (11), and
— a second type optical resonator cavity (12) having thermal means (13,14) for tuning the optical length of said cavity (12) by changing the temperature, and accordingly the refractive index of the cavity medium of said cavity (12).

2. The device (10) according to claim 1, **characterized** in that the cavity medium of said first type optical resonator cavity (11) is a gaseous material and the cavity medium of said second type optical resonator cavity (12) is a solid material.

3. The device (10) according to claim 2, **characterized** in that the cavity medium of said first type optical resonator cavity (11) is air and the cavity medium of said second type optical resonator cavity (12) is silicon.

4. The device according to any of the foregoing claims, **characterized** in that the thermal means (13,14) are based on ohmic, i.e. resistive heating.

5. The device according to any of the foregoing claims, **characterized** in that the tuning of the cavities (11,12) is arranged to be biased in

order to allow tuning towards shorter or longer wavelengths from the designed center wavelength.

6. The device (10) according to any of the foregoing claims, **characterized** in that the end mirror elements (15,16;16,17) of a cavity (11,12) are QWOT (Quarter Wave Optical Thickness) structures.

7. The device (10) according to any of the foregoing claims, **characterized** in that a mirror element (16) between two successive optical resonator cavities (11,12) is arranged to simultaneously function as an end mirror element for both of said cavities (11,12).

8. The device (10) according to claim 7, **characterized** in that the device (10) is a double-cavity interferometric device comprising altogether three end mirror elements (15,16,17).

9. The device (10) according to any of the foregoing claims, **characterized** in that the device (10) is manufactured on a semiconductor or compound semiconductor substrate material.

10. The device (10) according to claim 9, **characterized** in that the device (10) is manufactured on a Silicon-On-Insulator (SOI) wafer.

11. The device (10) according to any of the foregoing claims, **characterized** in that the device (10) is at least partly manufactured using silicon-surface micromachining techniques.

12. The device (10) according to any of the foregoing claims, **characterized** in that the device (10) is arranged to be used as Wavelength Add/Drop Multiplexer (WADM) device in an optical network utilizing Wavelength Division Multiplexing (WDM) techniques.

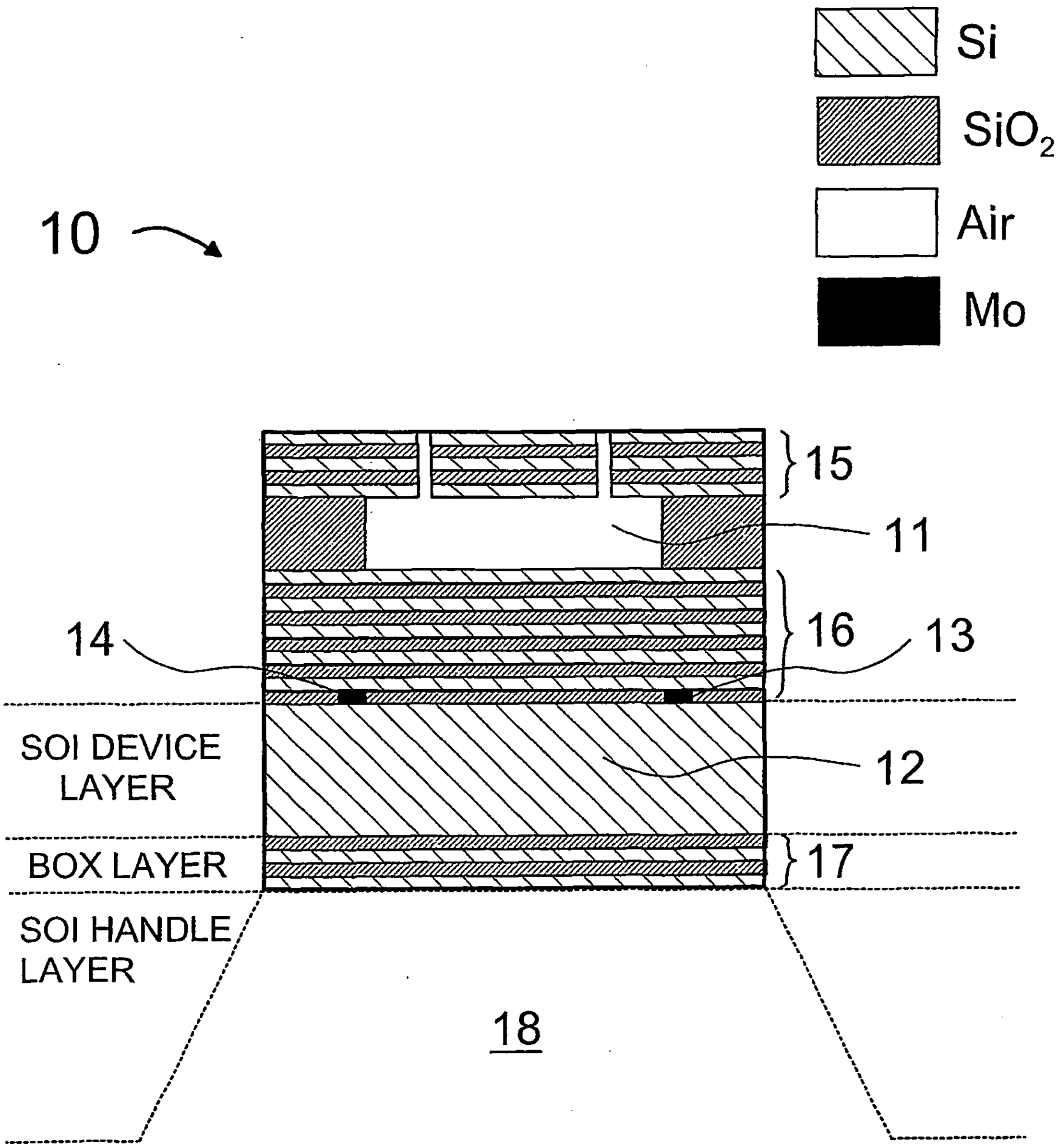
Si
SiO_2
Air
Mo
10
15
11
14
16
13
SOI DEVICE LAYER
12
BOX LAYER
17
SOI HANDLE LAYER
18

Fig.1

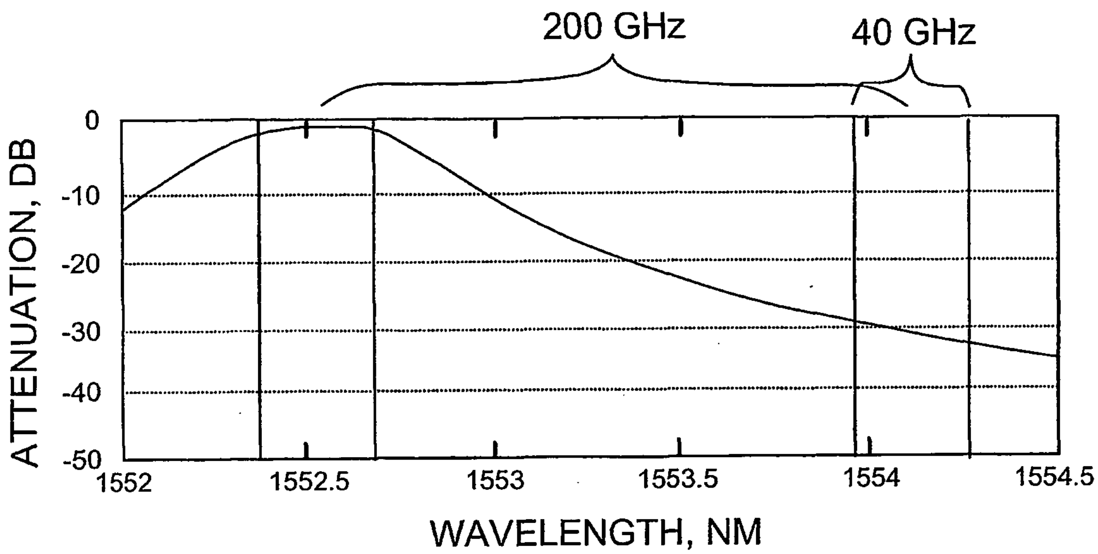
200 GHz
40 GHz
0
-10
-20
-30
-40
-50
ATTENUATION, DB
1552
1552.5
1553
1553.5
1554
1554.5
WAVELENGTH, NM

Fig.2

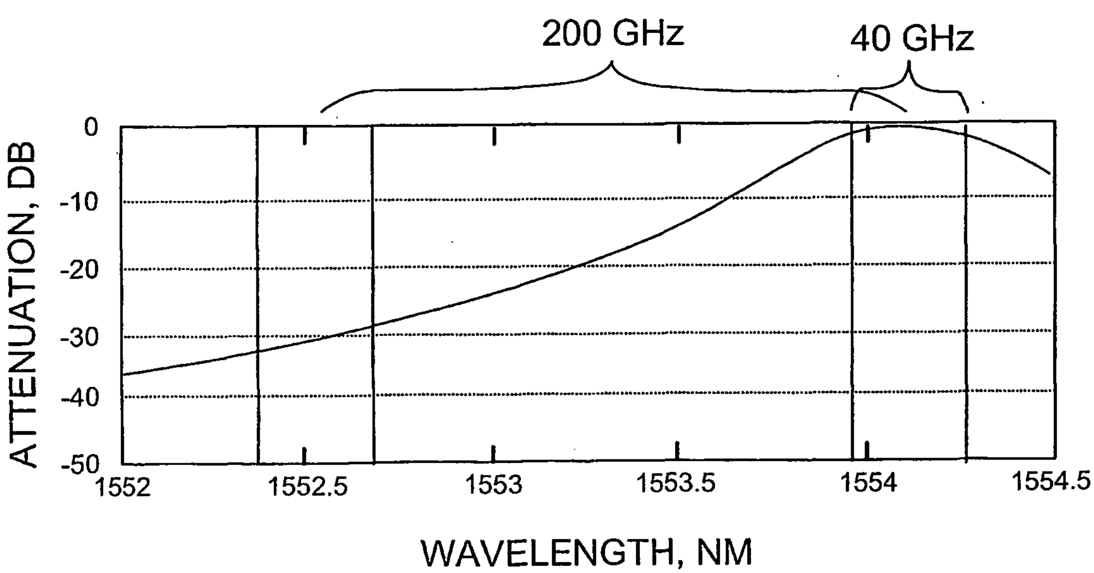
200 GHz
40 GHz
0
-10
-20
-30
-40
-50
ATTENUATION, DB
1552
1552.5
1553
1553.5
1554
1554.5
WAVELENGTH, NM

Fig.3

INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI 01/01115

A. CLASSIFICATION OF SUBJECT MATTER

IPC7: G02F 1/21, G02B 5/124, H01P 7/06
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

IPC7: G01B, G01N, G02F, H01P

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

SE,DK,FI,NO classes as above

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

WPI DATA

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	WO 0135485 A1 (MALCOLM, BRUCE ET AL), 17 May 2001 (17.05.01), page 1, line 15 - page 5, line 6; page 6, line 3 - page 8, line 3, figures 2-4, claims 1,2,11 --	1,2
A	DE 3923831 A1 (HARTMANN & BRAUN AG), 31 January 1991 (31.01.91), column 1, line 44 - column 2, line 10; column 2, line 63 - column 3, line 17, figure 3, claims 1,2 --	1,3,4
A	US 5345328 A (FRITZ ET AL), 6 Sept 1994 (06.09.94), column 1, line 48 - column 2, line 5; column 2, line 40 - column 3, line 36, figure 1, claims 1-7, 9,10 --	1

[X] Further documents are listed in the continuation of Box C. [X] See patent family annex.

* Special categories of cited documents:

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Date of the actual completion of the international search	Date of mailing of the international search report
18 July 2002	22 -07- 2002
Name and mailing address of the ISA Swedish Patent Office Box 5055, S-102 42 STOCKHOLM Facsimile No. +46 8 666 02 86	Authorized officer Igor Gazdik/SN Telephone No. +46 8 782 25 00

INTERNATIONAL SEARCH REPORT

International application No.
PCT/FI 01/01115

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5561523 A (BLOMBERG ET AL), 1 October 1996 (01.10.96), column 2, line 29 - line 67, figure 1, claims 1-12	1,2

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INTERNATIONAL SEARCH REPORT
Information on patent family members

06/07/02

International application No.
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		US 5059026 A	22/10/91
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